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**Opinion:** To advance sustainable stewardship, we must document not only biodiversity but geodiversity

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Rapid environmental change is driving the need for complex and comprehensive scientific information that supports policies aimed at managing natural resources through international treaties, platforms, and networks. One successful approach for delivering such information has been the development of Essential Variables for climate (1), oceans (2), biodiversity (3), and sustainable development goals (4) (ECVs, EOVs, EBVs, and ESDGVs, respectively). These efforts have improved consensus on terminology, and identified essential sets of measurements for characterizing and monitoring changes on our planet. In doing so, they have advanced science and informed policy. As an important but largely unanticipated consequence, conceptualizing these variables has also given rise to discussions regarding data discovery, data access, and governance of research infrastructures. Such discussions are vital to ensure effective storage, distribution, and use of data among management agencies, scientists, and policymakers (5, 6).

Although the current Essential Variables frameworks account for the biosphere, atmosphere, and some aspects of the hydrosphere (1–4), they largely overlook geodiversity—the variety of abiotic features and processes of the land surface and subsurface (7) (fig. 1). Analogous to biodiversity, geodiversity is important for the maintenance of ecosystem functioning and services (8), and areas high in geodiversity have been shown to support high biodiversity (9). Thus, consideration of geodiversity is an important part of developing nature-based solutions to global environmental challenges and demands for natural resources, particularly in relation to human wellbeing and ecosystem functioning.

And yet, despite many facets of sustainable development being underpinned by access to geological assets, key elements of geodiversity are yet to be incorporated into policy documents and international conventions. We therefore propose Essential Geodiversity Variables (EGVs) describing features and processes of Earth's abiotic surface and subsurface, to advance science and sustainable stewardship, complementing the existing Essential Variables. These EGVs will enable more holistic and better-informed monitoring efforts, decision making, and responses to global change.

### **Broad Scope**

The scope of geodiversity covers a wide range of policy areas, including terrestrial and marine conservation, sustainable use of natural resources, public health, natural hazard management, recreation, and tourism (e.g., see the “Conserving Nature's Stage” (10) and geosystem services (11) concepts). For example, abiotic features, including geothermal springs, inspired the creation of the world's first national park, Yellowstone. This park aimed specifically to safeguard geodiversity, and a century later its geothermal springs were the discovery site for *Thermus aquaticus*, a bacterium containing a thermostable enzyme that is used to amplify DNA segments and is thus the foundation of modern gene technology.

Another illustration of the critical importance of understanding and monitoring geodiversity globally concerns resource extraction. Removal of natural resources can decrease geological or mineral diversity, negatively impact local ecosystems (due to toxic extraction methods), and conflict with human rights. Notably, mobile phones with touch screens contain 54 elements of the periodic table, many of which are unevenly distributed in nature around the world and thus represent resource security concerns. Continued resource extraction is essential for achieving the Sustainable Development Goals (SDGs), but trade-offs with biodiversity conservation and human rights need to be explicitly addressed. For example, the transition to renewable energy sources will require the extraction of new minerals (e.g. materials for solar panels), as will greater urbanization and fertilizers for enhanced food security (12). Some tools and concepts necessary for incorporating such trade-offs are already available but not commonly applied within the context of the SDGs, e.g. in form of the geosystem services approach (11).

And while some EGVs such as groundwater are already considered within international legislation (e.g. the EU Groundwater Directive), most are underrepresented or not effective over wider regions. For example, currently the only binding international convention specifically on soil conservation is the 1991 Alpine Convention's Soil Conservation Protocol (13) (fig. 1), which omits most of the Earth's surface. Similarly, extraction of sand—a key ingredient in building materials and electronics—remains largely unregulated, despite rising global demand for this finite resource and wide-ranging devastating environmental consequences resulting from its extraction (14). The demand for minerals is rising globally, yet their extraction lacks international governance (15). Meanwhile, extraction and storage of vast quantities of soil and rock that are by-products from mining metals, as well as associated land requirements, are currently not part of integrated broad-scale management frameworks (16).

### **Essential Variables**

In presenting the EGV concept, we aim to 1) complement and augment existing essential variables (ECVs, EOVs, EBVs and ESDGVs) (fig. 1); 2) improve global coordination of monitoring strategies; and 3)

advance communication between policymakers and geoscientists. To achieve these goals, we propose a framework for policymakers and scientists to guide future definitions of relevant measurements that capture the key elements of geodiversity. We define EGVs as abiotic state and process variables related to geology, geomorphology, soils, and hydrology (i) relevant to natural resource management and human wellbeing, conservation, or ecology; (ii) complementary to (and not duplicating) the other suites of Essential Variables; and (iii) feasible and cost effective to measure (fig. 1, table S2).

Some aspects of EGVs are already used by international conservation organizations; these provide a solid basis for further integrating EGVs into global treaties and international conventions. For example, the International Union for Conservation of Nature (IUCN) refers to the relevance of geodiversity for conservation of natural resources within three resolutions titled “Conservation of geodiversity and geological heritage,” “Valuing and conserving geoheritage within the IUCN Programme,” and “Conservation of moveable geological heritage.” Furthermore, the United Nations Educational, Scientific and Cultural Organization (UNESCO) recognizes the outstanding universal value of geodiversity elements with their inclusion in both the World Heritage List (in May 2019, 95 properties in 53 countries worldwide) and in the Global Geoparks Network (140 Geoparks in 40 countries, as of May 2019). Many protected areas have the preservation of geodiversity and geoheritage as a goal of their management planning, including the Spanish network of Biosphere Reserves, Australia’s New South Wales National Parks, and the U.S. National Park Service. Meanwhile, the Food and Agriculture Organization (FAO) coordinates a Global Soil Partnership that seeks to monitor the state of global soils and improve the governance and effectiveness of soil information.

Data and information products to measure changes in EGVs at management-relevant timescales are increasingly available and sometimes linked to global observatories, such as the Global Earth Observation System of Systems (GEOSS), with its Societal Benefit Areas (SBAs). However, these mainly cover natural hazards such as floods, earthquakes, and landslides (e.g. SBA disaster resilience). Where dangers are more diffuse or related to natural resource use, EGVs are not yet available (e.g. relating to global sand extraction and domestication of soil resources).

### **Making EGVs Work**

Overall, despite the clear global importance of geodiversity, very limited international efforts have been devoted to developing measures that support decision-making for supra-national and global policy targets and SDGs (though there have been efforts to do so in the past (17)). Geodiversity is highly relevant, for example, to the IUCN World Parks Congress, the World Conservation Congress, the Convention on Biological Diversity’s Aichi targets, SDGs and the Sendai Framework for Disaster Risk Reduction (also see table S1 and table S2 in the supplementary materials).

We advocate a holistic approach that recognizes and tracks the integrity of the abiotic and biotic components of geo- and ecosystems, as the most effective means to address global environmental challenges. Following the examples of Essential Variables for the climate (ECV), ocean (EOV), and biodiversity (EBV) communities, we recommend collaborative development of comprehensive and interoperable databases of geodiversity globally, following common protocols, a standardized terminology (e.g. controlled vocabularies) and a consistent metadata reporting. We further recommend forming an expert panel, for example within the Group on Earth Observation framework to further develop the conceptual framework of EGVs. Finally, we encourage better communication with policymakers about the importance of considering EGVs in international conventions and policy documents. This could be enhanced by applying a “geosystem services” concept, which would complement the successful ecosystem services concept whose use within a policy and international treaties context was advanced by the Millennium Ecosystem Assessment (11), and by applying the recently published International Panel on Climate Change (IPCC) communication recommendations.



We now have the technical capacity and experience from other scientific communities to describe abiotic characteristics of Earth's surface and subsurface, and to develop holistic and parsimonious measures of geo- and ecosystem structure, function, and risks. Attaining a sustainable circular economy and safeguarding our natural resources, while also accounting for population growth, further urbanization, and improved well-being, will require international consideration of material flows and their impacts across terrestrial and aquatic systems globally. This will entrench a more holistic approach to nature, improving our efforts to designate protected areas and enhance management of natural resources. Doing so is essential for safeguarding biodiversity, geodiversity, ecosystem and geosystem services in a rapidly changing world, and for integrating and balancing the economic, social, and environmental dimensions of sustainable development.

## CAPTIONS

Pic 1:

Mining is one example of human impact on geodiversity. Active mines cause a decrease in local biodiversity but in some cases they can provide an important habitat for specialised and rare species after the mine has been abandoned. Image credit: Shutterstock/1968

Pic 2:

Figure 1: Schematic proportions of the Earth covered by existing Essential Biodiversity Variables (EBV, green), Essential Climate Variables (ECV, light blue), Essential Ocean Variables (EOV, dark blue), and by our proposed Essential Geodiversity Variables (EGVs, orange). Although life occurs throughout the ocean environment, EOVs refer predominately to abiotic aspects such as ocean physics and biogeochemistry, which do not overlap with EBVs (by definition exclusively covering biotic aspects). Consequently, the EBV box does not extend across the whole Earth surface cover axis. Some Essential Variables do overlap, as indicated by the striped sections—e.g. zooplankton diversity is both an EBV and EOV, while surface water is both an ECV and EGV. Several major international conventions (right) monitor and assess networks associated with each Essential Variable concept.

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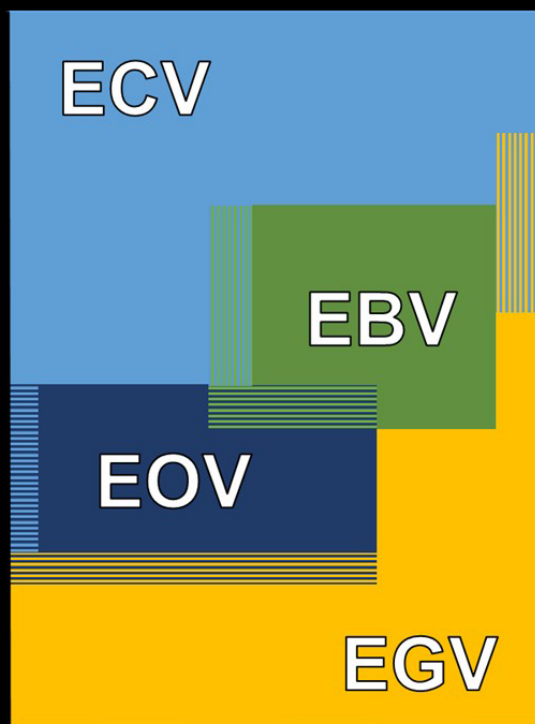
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ECV



GCOS  
IPCC  
UNFCCC  
WMO  
GTOS  
ESA-CCI  
CBD  
CITES

Global Climate Observing System  
Intergovernmental Panel on Climate Change  
United Nations Framework Convention on Climate Change  
World Meteorological Organization  
Global Terrestrial Observing System  
European Space Agency Climate Change Initiative  
Convention on Biological Diversity  
Convention on International Trade in Endangered Species of Wild Fauna and Flora

EBV



GEO BON  
GTOS  
IPBES

Group on Earth Observations Biodiversity Observation Network  
Global Terrestrial Observing System  
Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

EOVS



IUCN  
GOOS  
IOC-UNESCO  
IODE  
SOOS  
UNCLOS  
MSFD  
IOCCP

International Union for Conservation of Nature  
Global Ocean Observing System  
Intergovernmental Oceanographic Commission of UNESCO  
International Oceanographic Data and Information Exchange  
Southern Ocean Observing System  
United Nations Convention on the Law of the Sea  
Marine Strategy Framework Directive  
International Ocean Carbon Coordination Project

EGV



IGCP  
ISRIC  
SoilProt  
UNECE Water

International Geoscience Programme  
International Soil Reference and Information Centre  
Alpine Convention Soil Conservation Protocol  
United Nations Economic Commission for Europe Water Convention